Implications of SNO and BOREXINO results on Neutrino Oscillations and Majorana Magnetic Moments

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Abstract

Using the recent measurement of SNO salt phase experiment, we investigate how much the solar neutrino flux deficit observed at SNO could be due to ν_e transition into antineutrino. Our analysis leads to rather optimistic conclusion that the SNO salt phase data may indicate the existence of Majorana magnetic moment. The prospect for the future BOREXINO experiment is also discussed.

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In addition to the solar neutrino experiment at Super-Kamiokande (SK) [1], the recent neutrino experiments at Sudbury Neutrino Observatory (SNO) [2, 3, 4] and KamLAND [5] indicate that the long-standing solar neutrino problem, discrepancy between the prediction of the neutrino flux based on the standard solar model (SSM) [6] and that measured by experiments, can be resolved in terms of neutrino oscillations. Both the experiments, SNO and SK, probe the high energy tail of the solar neutrino spectrum, which is dominated by the ^8B neutrino flux. The water Cerenkov experiments from Super-Kamiokande (SK) [1] has observed the emitted electron from elastic scattering (ES) $\nu_x + e \rightarrow \nu_x + e$, $(\nu_x = \nu_e, \nu_\mu, \nu_\tau)$, while SNO has measured the neutrino flux through the charged current (CC) process $\nu_e + d \rightarrow p + p + e$, the neutral current (NC) process $\nu + d \rightarrow \nu + p + n$, and ES process given in the above. Very recently, SNO has measured the total active ^8B solar neutrino flux with dissolved NaCl in the heavy water to enhance the sensitivity and signature for NC interactions [4]. The results of the solar neutrino flux measured at SK and SNO are given in Table 1. Note that the SNO salt data I in Table 1 presents solar neutrino fluxes detected through CC, ES and NC without the constraint of an undistorted ^8B energy spectrum, while the SNO salt data II presents solar neutrino fluxes by adding the constraint. Based on a global analysis in the framework of two-active neutrino oscillations of all solar neutrino data and KamLAND result, the large mixing angle (LMA) solution is favored and oscillations into a pure sterile state are excluded at high confidence level [7]. It also appears that all non-oscillation solutions of the solar neutrino problem are strongly disfavored [8, 9].

The spin flavor precession (SFP) solution of the solar neutrino problem [10], motivated by the possible existence of nonzero magnetic moments of neutrinos, has attracted much attention before the KamLAND experiment. Although the KamLAND result excludes a *pure* SFP solution to the solar neutrino problem under the CPT invariance, a fraction of the flux suppression of solar neutrino may still be attributed to SFP [11]. In this respect, we believe that the detailed investigation on how much the flux suppression of solar neutrino can be attributed to SFP will lead us to make considerable progress in understanding the solar neutrino anomaly as well as the inner structure of the Sun. In addition, the observation of solar active antineutrino flux must be a signature for the existence of Majorana neutrinos and working of SFP inside the Sun [10, 12]. Recently, we have investigated a possibility to resolve the solar neutrino anomaly observed from the solar neutrino experiments in terms

Experiment	(interaction : flux $\Phi^{int}_{\rm exp}$)	
SK	$(ES: 2.35 \pm 0.08)$	
Old SNO	$(ES: 2.39 \pm 0.27)$	
	$(CC: 1.76 \pm 0.11)$	$(NC: 5.09 \pm 0.62)$
SNO salt I	$(ES: 2.21 \pm 0.30)$	
	$(CC: 1.59 \pm 0.11)$	$(NC: 5.21 \pm 0.47)$
SNO salt II	$(ES: 2.13 \pm 0.32)$	
	$(CC: 1.70 \pm 0.11)$	$(NC: 4.90 \pm 0.37)$

TABLE I: Solar neutrino flux measured at SK and SNO in the unit of $10^6 \rm cm^{-2} s^{-1}$.

of the combination of the neutrino oscillations and the neutrino spin-flavor conversions [13]. To achieve our goal, we have proposed a simple and model-independent method to extract information on ν_e transition into antineutrinos via SFP from the measurements of ^8B neutrino flux at SNO and SK, and showed how much the solar neutrino flux deficit observed at SNO and SK could be due to ν_e transition into antineutrino. As has been seen, in particular, our determination of the mixing between non-electron active neutrino and antineutrino is not affected by the existence of transition into a sterile state [13].

In this letter, we shall update the analysis based on the recent measurement of SNO salt phase experiment and investigate how large the transition of solar ν_e into non-electron antineutrinos could be responsible for the deficit of solar neutrino flux. As will be shown, our analysis leads to rather optimistic conclusion that the SNO salt phase data may indicate the existence of Majorana magnetic moment.

Let us begin by considering how the experimental measurement of the solar neutrino flux can be presented in terms of the solar neutrino survival probability. The excess of NC and ES can be caused not only by the active neutrinos but also by the active antineutrinos. The antineutrinos in question are mostly of the muon or tau types because of no observation of $\bar{\nu}_e$ [15]. Both $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ scatter on electrons and deuterium nuclei through their NC interactions, with different cross sections. Assuming the SSM neutrino fluxes, $\Phi_{\rm SSM} = 5.05^{+1.01}_{-0.81} \times 10^6 \rm cm^{-2} s^{-1}$, and the transition of ν_e into a mixture of active (anti-)flavor $\nu_{a(\bar{a})}$ and sterile ν_s that participate in the solar neutrino oscillations, one can write the SNO ES, CC and NC scattering rates relative to the SSM predictions in terms of the survival

probability [16, 17]:

$$
\begin{aligned}
R^{ES}_{\rm SNO} &\equiv \Phi^{ES}_{\rm SNO}/\Phi_{\rm SSM} = f_B \left[P_{ee} + r\sin^2\alpha\sin^2\psi(1-P_{ee})\right.\\
&\quad + \left.\bar{r}\sin^2\alpha\cos^2\psi(1-P_{ee})\right], \qquad (1)\\
R^{CC}_{\rm SNO} &\equiv \Phi^{CC}_{\rm SNO}/\Phi_{\rm SSM} = f_B P_{ee}, \qquad (2)\\
R^{NC}_{\rm SNO} &\equiv \Phi^{NC}_{\rm SNO}/\Phi_{\rm SSM} = f_B[P_{ee} + \sin^2\alpha(1-P_{ee})], \qquad (3)
\end{aligned}
$$

where $r \equiv \sigma^{NC}_{\nu_a}/\sigma^{CC+NC}_{\nu_e} \simeq 0.154$ and $\bar{r} \equiv \sigma^{NC}_{\bar{\nu}_a}/\sigma^{CC+NC}_{\nu_e} \simeq 0.114$ for a threshold energy of 5 MeV [18], and P_{ee} is the ν_e survival probability. Here $\sin^2\alpha$ indicates the fraction of ν_e oscillation to active flavor ν_a, whereas ψ is a mixing angle that describes the linear combination of the probabilities of ν_e conversion into ν_a and $\bar{\nu}_a$. Since there is a large uncertainty in the predicted normalization of $\Phi_{\rm SSM}$, arising from the uncertainty in the $^7Be + p \rightarrow\ ^8B + \gamma$ cross-section, we have introduced a constant parameter f_B to denote the normalization of the ^8B neutrino flux relative to the SSM prediction. We assume a common survival probability for all the three measurements. Using the measured values of the rates R, we can estimate the allowed regions of the quantities f_B, P_{ee} and α. In particular, the fraction of ν_e oscillation to ν_a is described by the relation [16, 17],

$$\sin^2\alpha = \frac{R^{NC}_{\rm SNO} - R^{CC}_{\rm SNO}}{f_B - R^{CC}_{\rm SNO}}. \qquad (4)$$

Imposing the SSM constraint $f_B = 1 \pm 0.18$ [16] and the experimental results for the ratios $R's$, we obtain

$$\sin^2\alpha = 1.05 \pm 0.32. \qquad (5)$$

We see that the evidence for transitions to active neutrinos is at the 3.3σ C.L., but large sterile fractions are still allowed.

From Eqs. (1,2,3), we see that the mixing angle ψ is related with the measured neutrino fluxes as follows:

$$r\sin^2\psi + \bar{r}\cos^2\psi = \frac{R^{ES}_{\rm SNO} - R^{CC}_{\rm SNO}}{R^{NC}_{\rm SNO} - R^{CC}_{\rm SNO}}, \qquad (6)$$

where we have assumed that $\sin^2\alpha$ is non-zero. The expression (6) shows that the determination of the mixing angle ψ is independent of nontrivial $\sin^2\alpha$, and the precise measurements of $R^{ES}_{\rm SNO}, R^{NC}_{\rm SNO}, R^{CC}_{\rm SNO}$ as well as the values of r and $\bar{r}$ make it possible to see how much the solar neutrino flux deficit can be caused by SFP. We note that any deviation of the value

of $\sin^2\psi$ from one implies the evidence for the existence of ν_e transition into non-sterile antineutrinos, and if there is no transition of solar neutrino due to the magnetic field inside the sun, the left-hand side of Eq. (6) should be identical to the parameter r. To obtain the values for the right-hand side of Eq. (6), we consider two combinations of the experimental results measured through CC, ES and NC interactions :

$$\begin{aligned}
&\text{(a)} \;\; \text{SNO salt data phase I} \; : \; (\Phi^{CC}_{\text{SNO}}, \; \Phi^{ES}_{\text{SNO}}, \; \Phi^{NC}_{\text{SNO}}), \\
&\text{(b)} \;\; \text{SNO salt data phase II} \; : \; (\Phi^{CC}_{\text{SNO}}, \; \Phi^{ES}_{\text{SNO}}, \; \Phi^{NC}_{\text{SNO}}),
\end{aligned}$$

and then the results are given as follows:

$$\text{Eq. (6)} \Rightarrow \begin{cases} \text{(a)} \quad 0.171 \pm 0.089 \; , \\ \text{(b)} \quad 0.134 \pm 0.105 \; . \end{cases} \tag{7}$$

Since $\bar{r} \leq r\sin^2\psi + \bar{r}\cos^2\psi \leq r$, we notice that the left-hand side of Eq. (6) prefers to lower sides of Eq. (7), and leads to

$$\sin^2\psi = \begin{cases} \text{(a)} \quad 1.43 \pm 0.33 \; , \\ \text{(b)} \quad 0.51 \pm 0.39 \; . \end{cases} \tag{8}$$

From Eq. (8), we see that both pure active neutrino oscillation and neutrino oscillation+SFP are allowed for the SNO salt data I (combination (a)) within 2σ level, whereas the SNO salt data II (combination (b)) shows that the existence of solar ν_e transition into $\bar{\nu}_a$ is at 1.3σ although the pure active neutrino oscillation is allowed within 2σ. Therefore, only new SNO data constrained by undistorted ^8B neutrino spectrum implies an evidence for the existence of the spin-flavor transition due to Majorana neutrino magnetic moment in the solar neutrino fluxes. We note that the main reason for $\sin^2\psi > 1.0$ in the case of (a) is due to large deviation of CC flux from ES one. Thus, the precise determination of the central values of each flux as well as reduction of the uncertainties will lead us to precisely probe the existence of the solar neutrino transition into antineutrino in the above way. In this analysis, we have taken into account only SNO salt phase results. If we replace the SNO ES rates with the SK ES one as done in [13], the value of $\sin^2\psi$ comes out to be very large because the flux of SK ES is rather larger than those of SNO salt ES as shown in Table I.

Let us briefly discuss the prospect for future experiment, BOREXINO, which will detect the medium energy ^7Be,CNO and pep solar neutrinos through ES interaction [19]. Assuming that the observed flux deficit of solar neutrinos is due to the combination of neutrino

oscillations and SFP transitions, we can predict $R^{ES}_{\rm BOR} = \Phi^{ES}_{\rm BOR}/\Phi_{\rm SSM}$. In order to do that, we first determine the survival probability of the medium energy neutrinos by comparing Homestake event rate [20] with the SNO CC result. Since the fractional contributions of the high energy ^8B and the medium energy neutrinos to the ^{37}Cl signals are 76.4% and 23.6%,respectively, the measured rate divided by the SSM prediction for the Homestake experiment $R_{\rm Cl}$ with oscillations is given by

$$R_{\rm Cl} = 0.764\ f_B P^B_{ee} + 0.236\ P^M_{ee} \tag{9}$$

where P^B_{ee} is the survival probability for ^8B neutrinos, whereas P^M_{ee} is that for the medium energy neutrinos. Since $f_B P^B_{ee}$ is equivalent to $R^{CC}_{\rm SNO}$, we can obtain the numerical value of P^M_{ee} by using the experimental results for $R^{CC}_{\rm SNO}$ and $R_{\rm Cl}$:

$$P^M_{ee} = \begin{cases} \text{(a)} \quad 0.409 \pm 0.105\ , \\ \text{(b)} \quad 0.338 \pm 0.105\ . \end{cases} \tag{10}$$

Similar to the SNO measured rates, by allowing both neutrino oscillation and SFP transitions, the BOREXINO ES rate relative to the SSM predictions in terms of the survival probability is presented as

$$R^{ES}_{\rm BOR} = P^M_{ee} + \sin^2\alpha(r\sin^2\psi + \bar{r}\cos^2\psi)(1 - P^M_{ee})\ , \tag{11}$$

where $r \simeq 0.213$ and $\bar{r} \simeq 0.181$ for ^7Be neutrinos. Using the above results Eqs.(5,8), we can obtain

$$R^{ES}_{\rm BOR} = \begin{cases} \text{(a)} \quad 0.549 \pm 0.117\ , \\ \text{(b)} \quad 0.475 \pm 0.116\ . \end{cases} \tag{12}$$

It can be interesting to compare the above with the predictions for pure neutrino oscillation cases ($\sin^2\psi = 1$) which are given by

$$R^{ES}_{\rm BOR} = \begin{cases} \text{(a)} \quad 0.541 \pm 0.116\ , \\ \text{(b)} \quad 0.486 \pm 0.117\ . \end{cases} \tag{13}$$

We note that the main uncertainties in (12,13) are due to the uncertainty in P^M_{ee}. From the above results, we see that it might be difficult to discriminate between pure oscillation solution and oscillation + SFP solution unless the future BOREXINO experiment measures $R^{ES}_{\rm BOR}$ with the uncertainty $\delta R^{ES}_{\rm BOR} \sim 2-3\%$. If the future SNO experiment could reduce

the errors in the flux measurements to about 50%, then the uncertainty on $\sin^2\psi$ becomes $\delta\sin^2\psi \simeq$ (a)0.17 (b)0.19 and if the errors in P^M_{ee} could be reduced to 30%, the uncertainties in the prediction for $R^{ES}_{\rm BOR}$ becomes about $\delta R^{ES}_{\rm BOR} \simeq 0.05$ which is still a little large to see whether there exists an evidence for the existence of spin-flavor transition from BOREXINO experiment. However, since oscillation + SFP solution prefers lower value of $R^{ES}_{\rm BOR}$, if the future BOREXINO will measure $R^{ES}_{\rm BOR} \leq 0.37$, it might be an indirect evidence for the existence of Majorana neutrinos and working SFP mechanism in the Sun. In addition, we hope that the future BOREXINO experiment would make us to decide which case of SNO data set between (a) and (b) is more relevant.

In summary, we have examined in a simple and model-independent way how much the ν_e transition into antineutrinos could be in the solar neutrino flux. The SNO salt data constrained by an undistorted ^8B energy spectrum indicates the existence of Majorana magnetic moment and working SFP mechanism within about 1σ level, while the SNO salt data without that constraint allows both pure active neutrino oscillation and the effect of SFP within 2σ level. The prospect for the future BOREXINO experiment has been discussed.

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